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ABSTRACT

Two studies were conducted to describe how students perform direct current (D-C) circuit problems. It was hypothesized that problem solving in the electricity domain depends largely on good visual processing of the circuit diagram and that this processing depends on the ability to recognize when two or more electrical components are in series or in parallel, even if the drawings diverge from the canonical ones such as those which are largely taught. The first study examined how college students (N=10) recognized a given circuit among different circuit drawings. Results indicate that these students were able to recognize circuits in series or in parallel only if they have canonical shapes, such as those taught in class or drawn in textbooks. Tenth-grade students (N=22) participated in the second study which demonstrated how the current conservation law at a junction point is applied to a D-C circuit. These students solved the same problem by different procedures which depended directly on how their knowledge was memorized, indicating that current conservation is associated with a specific circuit similar to a canonical one, formulated as a mathematical relation without physical content, or formulated as a law applied to a junction point. Implications for science instruction are discussed. (JN)

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PROBLEM SOLVING IN ELECTRICITY

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PROBLEM SOLVING IN ELECTRICITY

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Abstract.

In this study we have performed two kinds of experiments to describe how students solve D-C circuit problems. The problem statements are given together with diagrams and students need to process the information displayed on the circuit diagram. The first study have shown that students were able to recognize circuits in series or in parallel only if they have canonical shapes, such as those taught in class or drawn in textbooks. They lack the skill useful to analyze the circuit topology. In the second study, we have shown how the current conservation law at a junction point is applied to a D-C circuit. The useful knowledge appears to be stored in memory under three main schemata: the first is associated with specific circuit, the second with a mathematical relation without any physical sense and the third is like the physicist's.From these studies some teaching suggestions are given.

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1. - INTRODUCTION.

During these last few years, problem solving studies in physics have been well developped (1). This research interests all at once cognitive psychologists and science education researchers. However, following the scientist's point of view, the research can be either descriptive (2) or prescriptive (3). Here we will have a descriptive approach which will cast some light on possible teaching applications.

Problem solving in electricity has been seldom studied. So far most of problem statements has been drawn from mechanics. D. GENTNER (4) studied how two different analogies (hydraulic and crowd models of current) influence solving and M. RILEY et al.(5) showed how students are confused by different electricity concepts such as voltage and resistance. But descriptive studies showing how students solve ordinary electricity problems such those found in a textbook have not yet been made. The part of electricity retained by us was electrical circuits.

The knowledge useful to solve electrical circuit problems is not too large. Only four concepts are relevant (current, resistance, potential difference and emf) and two laws are sufficient to describe the functioning of such a circuit: the so-called Kirchhoff's laws. However electrical circuit problems have specific characteristics: the statement includes generally a circuit diagram which represents pictorially some symbolic information useful to solve the given problem. If a student cannot process this information, he will certainly fail. The information is displayed under both a local and a global aspects.First, specific values are locally assigned either to different circuit components (e.g. 20 Ω for a resistor, 6 V for a battery) or electrical quantities (for instance, 0.3 Amp. in a specific branch). They are usually written on the diagram just beside the element under consideration. But a global information is given as well: it is the respective position of each component in the circuit and how each of components is related to the rest of the circuit. In a circuit, there are components in series and/or in parallel, so that the most complex circuit can be decomposed into more elementary circuits. When this analysis is done, the solving becomes easier since the subject has replaced a complex circuit by a combination of several

elementary circuits. However this ability depends on the subject's expertise level. D. EAGAN and B.J. SCHWARTZ (6) showed that in electronics electronicians considered asexperts are able to recognize some structural circuits in a complex circuit whereas novice does not see anything except different unrelated devices.

Our central hypothesis is that problem solving in the electricity domain depends largely on a good visual processing of the circuit diagram. This processing depends on the ability to recognize when two or more electrical components are in series or in parallel, even if the drawings diverge from the cannonical ones such as they are largely taught.

INSERT FIGURE 1 ABOUT HERE.

Students must be aware that circuit diagrams have topological properties and not metric ones. But visual processing is often not enough to succeed. The way knowledge is organized plays an important part as well. If we consider after D.E. RUMELHART (7) that our knowledge is built on schemata, we should also try to know how the knowledge in electricity is organized in the student's long term memory, in other words to know what schemata are activated for a given problem and what their content is.

In this paper we are presenting two kinds of experiments. The first series described in paragraph 1 allowed us to study how students solve problems which need a great deal of picture processing. The results will be discussed in paragraph 2. Paragraph 3 presents the second experiment and the result on different student's schemata relevant to the 1st Kirchhoff's law. In paragraph 4, we discuss some suggestions for an electricity teaching which would allow students to improve their performance in the considered domain.

1. - EXPERIMENTS ON VISUAL PROCESSING.

1. 1. - Recognition tasks.

These experiments deal with picture processing. We asked 10 first-year college students to recognize a given circuit among different circuit drawings. The students who were just finishing to learn D-C circuit properties were to analyze the circuits and say what circuits were similar to the reference circuit. The task given on Fig.2 was a paper-and-pencil task and we requested students to think aloud while they were solving. Their verbalizations were recorded on audio-tape and the written papers were collected.

INSERT FIGURE 2 ABOUT HERE.

The circuits shown on Figure 2 were composed either only by resistors (Fig.2-a) or by resistors and batteries (Fig.2-b).

1 - 2 Equivalent resistance task.

In this task, the same students as previously were asked to calculate an equivalent resistance between two terminals, knowing the resistance value of each resistor composing the circuit.

INSERT FIGURE 3 ABOUT HERE.

The circuits present different resistor settings,some of them being voluntarily confusing. For instance, resistors in series were drawn parallel (see circuit (1) on Fig.3) or resistors in parallel such as the 3Ω, 6Ω and 2Ω resistors, were not drawn parallel (see circuit (4) on Fig.3). Again we recorded the students verbalizations while they were solving the given task and we collected their written work. We were interested in how students grouped resistors together to calculate the equivalent circuit resistance. For this problem, it was

obvious that students had to remember formulae giving the equivalent resistance of resistors in series and in parallel. But this recall from memory was not a real difficulty for students. As we will see when we discuss the results the difficulty was to identify correctly what resistors are in series or in parallel, indepently of what is drawn diagrammatically.

2. - RESULTS OF EXPERIMENTS ON VISUAL PROCESSING.

2 - 1 Recognition tasks.

The number of correct answers for both tasks presented on Fig.2 is given on Fig.4.

INSERT FIGURE 4 ABOUT HERE.

The results show that whatever the circuit under consideration we never get 100 % of right answers. In spite of the relative simplicity of the task, the students are not able to recognize similar circuits drawn under different shapes. But the protocol analysis shows strikingly the differences in the way students solve each problem according to the composition of the circuits (whether they are made in resistors or not).

To solve the first task (Fig.2-a) where circuits are only composed of resistors, students either look carefully at the diagrams and try to analyze the circuit features such as the junction points or they transform the given circuits by geometric operations. These transformations are of two types: some students redraw the circuits into circuits more or less similar to the reference circuit (in this case with a rhombus shape) or they transform all the circuits, including the reference circuit, into circuits which look more familiar to students such as rectangular circuits. Then, they try to match them. The important result here is that the geometric diagram

transformations are efficient procedures to recognize equivalent circuits when the circuits are relatively simple.

In the first recognition task the failures seem to come from bad feature analysis rather than from errors in the geometric transformations made by students to get new circuit diagrams.

However for the second task (Fig. 2 b), if two students still use geometric transformation, the other students do not give any more explanations as to their way to find a solution. Instead, just after having looked at the circuit., they often give a wrong answer directly together with some interesting remarks. For the circuit (3) of Fig 2-b students say that this circuit is different from the reference circuit because there are batteries in series or even resistors in parallel (that is wrong, strikly speaking). Now the reference circuit and the circuit 3 are identical: they have the same topology. But the circuit (3) leads students to give a wrong answer with an unsound proof. The battery combination in circuit (3) is drawn like the canonical circuit of batteries in series and the circuit with both resistors looks like the canonical circuit of resistors in parallel. These canonical circuit shapes are largely taught and found extensively in the textbooks.

From the students' answers to the second recognitios task, we see that procedures are less systematic than the ones used in the first task. When the circuit becomes more complex, the students are confused by the circuit surface features. In fact they match directly the circuit under consideration with memorized patterns such as the canonical circuits taught in class. These memorized canonical circuits play the part of prototype, concept found in cognitive psychology (8).

2 - 2 - Equivalent resistance task

The global result of number of correct answers for each circuit is given Fig. 5.

INSERT FIGURE 5 ABOUT HERE

The more resistors in the circuit, the less students succeed in the task. The answer analysis shows that errors come from a poor identification of resistors in series or in parallel. Table 1 gives the list of incorrect groupings made by students for each circuit. Again the students are confused by the diagram pictures. For instance the students group in series resistors which are lined up such as the 2 and 4 Ω resistors in the circuit 3 or the 5 and 2 Ω resistors in the circuit 4. In the same way, they consider as resistors in parallel only resistors geometrically parallel, such as the 3 and 6 Ω resistors in the circuit 4, whereas the 2 Ω resistor is said to be in series with the 5 Ω resistor.

Again, as in the previous experiments, students consider only resistor combinations which look like canonical circuits. We can say at this point that students recognize specific circuits only by their geometrical shape, and not through a carreful analysis of how each electric component is related to its nearest neighbors.

3 - PROBLEM ON THE CURRENT CONSERVATION.

3 - 1 - Description of the task.

The problem is presented on Fig.6. It deals only with the current conservation at each junction: the unknown current can be determined if all other currents are known.

INSERT FIGURE 6 ABOUT HERE.

However to get the answers, the student should infer that the current is 1.5 Amp in EF and 1 Amp in BA or HG, since no current value is written near these parts of the circuit. This inference is possible if the student knows that the current flowing in a circuit part is the same at any point between two terminals.

The problem was given to 22 10^{th}-grade students, once they had been taught on current, voltage and the different properties of these two concepts. The students belonged to four different classes. The technique used was the same as the one described previously: thinking aloud, recording on audio-tape and protocol analysis.

Only 6 students out of 22 succeeded in finding all requested currents. As we wanted to study how each student has applied the current conservation law in a specific case, we listed the stated mathematical relations (eg. equalities or additions) between two or more currents. So we have been able to classify the different stated relations among the following categories:

- Current equality
  - in geometrically parallel parts (as in BC and in FG)*
  - in parts in series * (as in BAHG or in DEF)
  - in connected parts (as in the FGBC loop).
- Current addition
  - in disconnected parts (e.g. $I_{BC}=I_{DC}+I_{FG}$)
  - in connected parts(e.g. $I_{BC}=I_{BD}+I_{DE}+I_{EG}$)
  - at a junction point(1)
    - of only 2 currents
    - of n currents*

This classification shows that in addition to correct relations (here noted *), students often evoke uncorrect relations as well.

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(1)We had to separate the current additions at a junction point into two categories because some students had applied the 1^{st} Kirchhoff's law to only 3 currents even if there are 4 currents at the junction point.

3 - 2 - Discussion.

Since 16 students failed to find the requested currents, we can say that for them there has been no transfert between what is taugt by the teacher and the problem itself. But this conclusion is insufficient because the protocol analysis shows more: the students have representations of the current conservation which are intriguing.To solve the problem , they instantiate a problem schema which is directly related to the way they have understood the current conservation at a junction point. These schemata can be grouped into three main schemata :

- a canonical circuit schema,
- a current/voltage schema,
-a junction point schema.

3 - 2 - 1 - Canonical circuit shema

This schema is very specific : the current conservation law is directly associated with a specific circuit having a prototypical diagram (Fig. 7). The circuit is composed of two parts : the "main circuit" including the battery and a "branched circuit" made of only two resistors in parallel.

INSERT FIGURE 7 ABOUT HERE

For this very specific circuit , the current conservation law takes the form $I_{main} = I_1+I_2$ where I_1 and I_2 are the currents in both branches in parallel. The "main circuit" sub-schema comes from the following characteristics :

- some students forget completely about the existence of BAHG and don't talk about it while solving;

-some others say that $I_{BC}=I_{FG}=I_{BG}$ (the current is constant along the "main circuit");

-and last but not least, they speak in terms of "main circuit".

The existence of a "branched circuit" sub-schema has been infered from some stated current additions such as $I_{BG}=I_{DC}+I_{DE}$,or when students analyze the circuits in terms of branches or even of "bifurcations". The comparison between the canonical circuit and the given diagram shows that both circuits are really very different but the novices, if they well recognize this difference in their shapes

don't see any difference as regards to their topological properties and their electrical characteristics. They lack some flexibility to make a correct analysis of the given diagram.

3 - 2 - 2 - Current/Voltage schema

Other students don't discriminate between current and voltage. For example, they equalize the currents in branches in parallel (e.g. $I_{GB}=I_{AH}$) or they add currents in series (e.g. $I_{DF}=I_{DE}+I_{EF}$) as if they considered voltage instead of current. The students remember the mathematical relation stucture of equality or addition but they don't remember with which quantities they are associated. They know formulae they apply independently of their applicability conditions. This procedure leads obviously to wrong answers.

3 - 2 - 3 - Junction schema

For both previous schemata, the knowledge relative to the 1st Kirchhoff's law is quite distant from the physicist's knowledge. It is associated either with a specific circuit diagram or with a mathematical relation with no physical sense. Only 8 students have a knowledge of current conservation close to the physicist's: they apply it to a junction point. They calculate an unknown current if they know the other currents in using an additive relation. However for two students this knowledge is limited to a relation between only 3 currents whatever the number of branches coming to the junction point under consideration. For example, in order to determine I_{CF}, a student considers the point F and says "We have $I_{DF}+I_{CF}=I_{FG}$" although there are 4 branches at F. The other students use the correct conservation law with its most general fofmulation whatever the branch number at the junction point.

In summary, we have seen that students try to solve the same problem by different procedures which depend directly on how the knowledge is memorized. So the current conservation is associated with a specific circuit similar to a canonical one, or it is formulated as a mathematical relation without physical content or as a law to be applied to a junction point.

4 - TEACHING SUGGESTIONS.

The results of three experiments reported here on problem solving in electricity lead us to question the present elctricity teaching and to make some suggestions to improve this teaching. The recognition and equivalent resistance tasks have clearly shown that students have serious difficulties in analyzing correctly a circuit and seeing what components are in series or in parallel. This analysis is made easier if diagrams look like the largely taught canonical circuits because the students recognize the form of what they have already learnt in class. But they don't understand what physicists call circuits in series or in parallel. These concepts are related to electrical and topological properties, and not to specific circuit drawings. At this point, the question to put out is "Is it judicious to introduce symbolism at the beginning of an electricity teaching?". Symbolism is really an advantage for electrical networks or forelectronics circuits where the large number of components makes it necessary to use a graphic code. For beginners, it is important that teachers should stress the topological circuit properties in presenting different equivalent circuit diagrams and that students discover the electrical properties of specific circuits such as the circuits in series or in parallel rather than their canonical form.

Another suggestion can be made from the descriptive study of solving of the current conservation problem. We have seen that, for most novices, knowledge related to a basic physics principle (the current conservation) is very different from the physicist's. Instead of being sufficiently general to be applied to any problem, it appears either to be specific to a particular circuit or to a junction point with only 3 branches. In both cases, students don't realize that their specific current conservation law cannot be applied to a circuit different from the prototype. We think that it is a direct teaching outcome. The teachers usually prefer first to present simple examples on which they design one or several learning sequences, then they generalize. Now what a student remembers is often the specific cases rather them the general ones, so that he/she lacks the useful formulations in all their generality to solve a problem which differs from the specific cases taught in class. So we think that it is important to present the general case through different examples to show all the richness of a physics principle rather than to accumulate specific cases.

5 - CONCLUSION.

In this paper, we have presented some descriptive research on problem solving in electricity. We have seen that failure can come from different origins: either a poor analysis of information displayed under a symbolic form such as on a diagram or an incomplete knowledge of a physics law which turns out to be memorized under a formulation too specific to be applied to any problem. In order to improve the student's performance, we have to take these results into account and design instructionnal sequences which stress the topological properties of any circuit. We have to develop material which allows students to understand electricity principles in their whole physical meaning: utility, applicability conditions and formulation. But we have also to think what cognitive skills are useful to solve problems including diagrams: what learning would help students to process visually a diagram in relation with a knowledge base in electricity ?

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS.

Fig. 1 - Series and parallel canonical circuits.

Fig. 2 - Circuits used in the recognition tasks.
2 - a - Circuits with resistors.
2 - b - Circuits with resistors and batteries.

Fig. 3 - Circuits used in the equivalent resistance task.

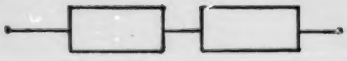
Fig. 4 - Number of correct answers at both recognition tasks.

Fig. 5 - Number of correct answers at the equivalent resistance task.

Fig. 6 - Problem on the current conservation law.

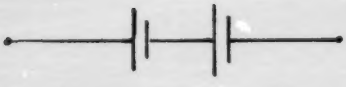
Fig. 7 - Canonical circuit used by some students.

CIRCUITS IN SERIES



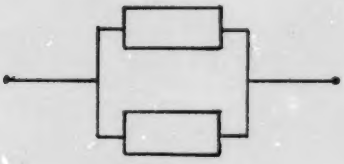
Dipoles

Resistors



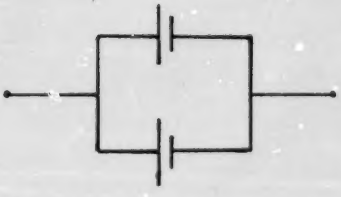
Batteries

CIRCUITS IN PARALLEL



Dipoles

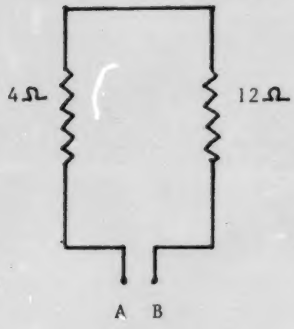
Resistors



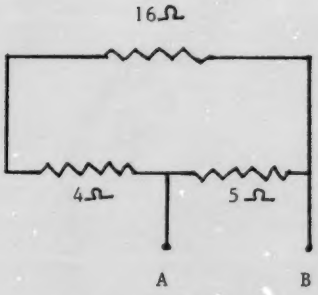
Batteries

Fig. 1

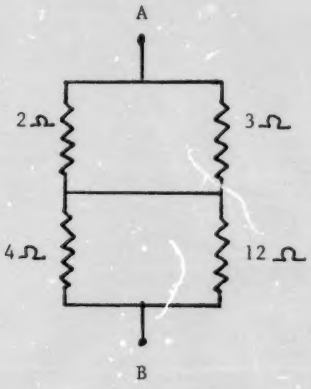
EQUIVALENT RESISTANCE TASK



(1)



(2)



(3)

(4)

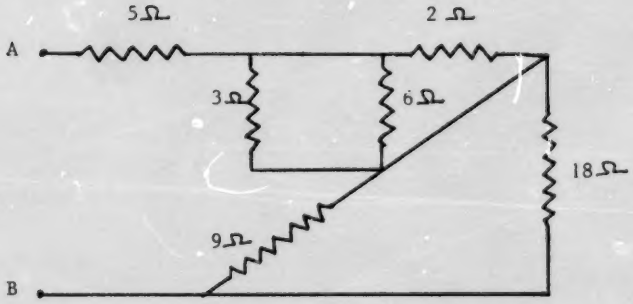
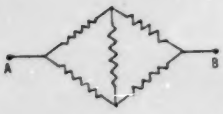
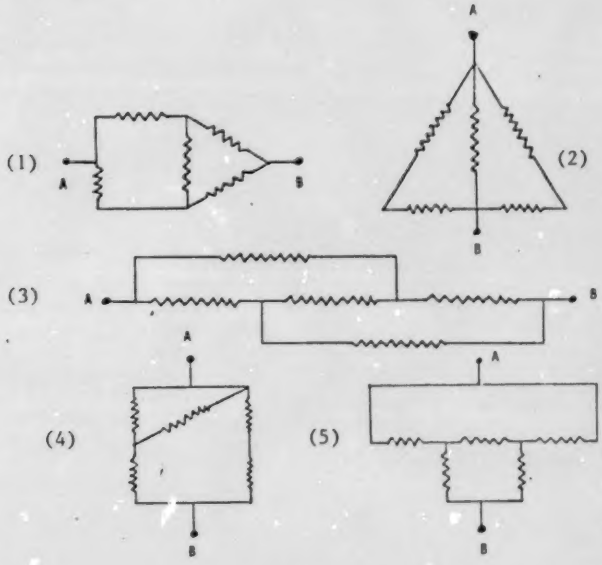


Fig. 3

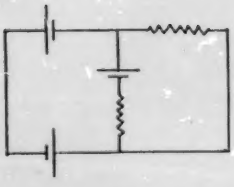
2 - a CIRCUITS WITH RESISTORS



Reference circuit



2 - b CIRCUITS WITH RESISTORS AND BATTERIES



Reference circuit

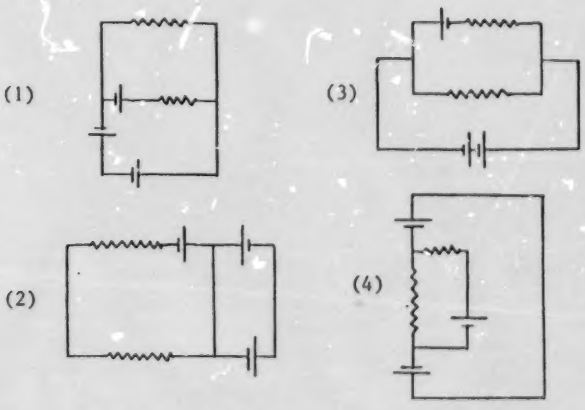
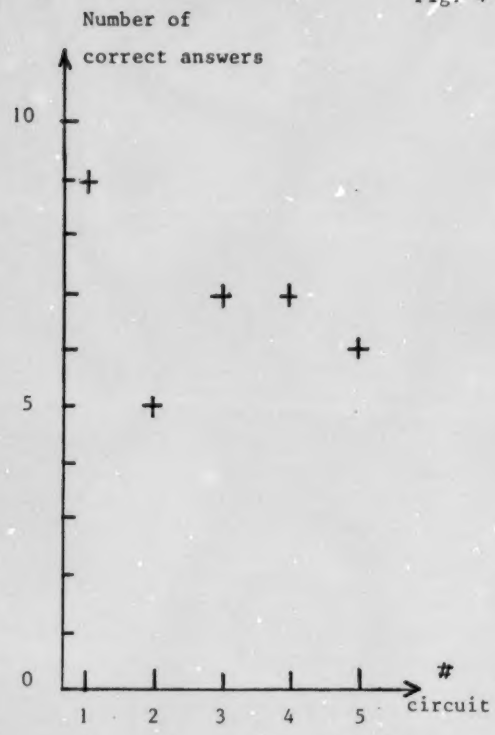
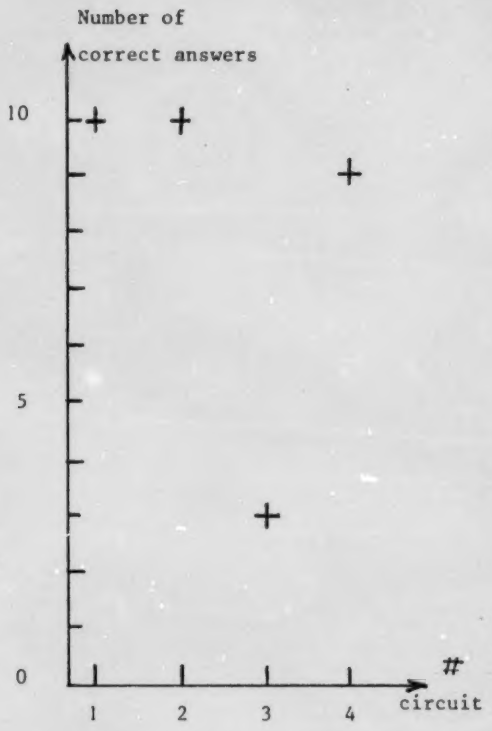


Fig. 2

Fig. 4



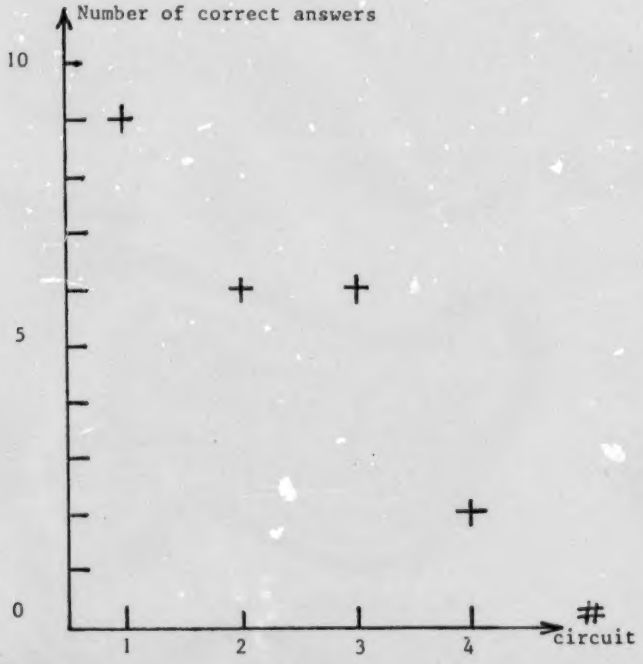
CIRCUIT WITH RESISTORS

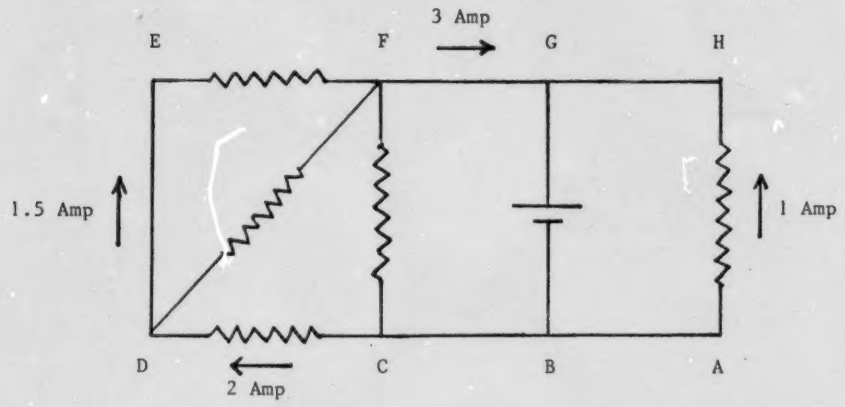


CIRCUIT WITH RESISTORS AND BATTERIES

Fig. 5

EQUIVALENT RESISTANCE





Find the currents in BC, GB, DF, CF.

Fig. 6

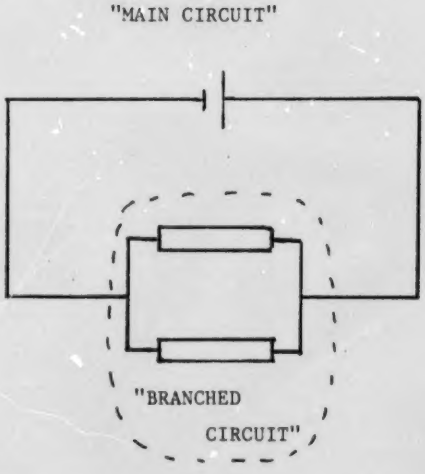


Fig. 7

TABLE I

INCORRECT GROUPINGS

Circuit 1	4 and 12Ω in parallel
Circuit 2	4 and 5Ω in series or 4, 5 and 16Ω in series
Circuit 3	2 and 4Ω in series and 3 and 12Ω in series
Circuit 4	Only 3 and 6Ω in parallel and 5 and 2Ω in series or 18Ω in parallel with any combination of all other resistors